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Annealing effect on the nonradiative carrier recombination in AlGaAs/GaAs investigated by a piezoelectric photothermal spectroscopy

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ABSTRACT

Electron non-radiative recombination process of photoexcited carriers in as-grown and annealed n-$Al_{0.2}Ga_{0.8}As$/GaAs hetero-structure samples are investigated by using a piezoelectric photothermal spectroscopy (PPTS). The PPT signal above the band-gap energy of GaAs substrate decreased when the sample was annealed at 815°C. In the frequency dependent measurements, the deviations from $1/f$ linear function are clearly observed in the AlGaAs/GaAs samples. This critical deviation frequency was found to shift to the lower frequency region by annealing. Our experimental results are explained by assuming that the sample annealing generates an unknown deep level in AlGaAs epitaxial layer region and this level effectively traps the photoexcited carriers non-radiatively.

INTRODUCTION

Pseudo-binary compound semiconductor AlGaAs is widely used for quantum electronic devices such as the light emitting diodes (LED) and the hetero bipolar transistor (HBT). Intrinsic deep defect levels in this material are known to cause a degradation of such devices. They trap the free carriers, and thus high frequency operation of electronic devices are seriously influenced. Annealing process followed by an ion-implantation is a most important process in the device fabrication. Since this annealing process affects a formation and a destruction of deep defect levels, it is very important to understand an annealing effect on the carrier generation and recombination properties through deep defect levels.

The recombination process of photoexcited carriers is commonly investigated by a photoluminescence (PL) method. This is available technique to understand a light emission mechanism such as band to band, band to impurity level, and impurity to impurity levels transitions. However, the recombination processes of carrier through the deep levels is mainly non-radiative recombination. A strong electron lattice interaction affects these carrier transitions. The PL method can detect only a radiative recombination process. Therefore, it becomes important to establish an alternative experimental technique to investigate such transitions.

Recently, we have developed the piezoelectric photo-thermal (PPT) spectroscopy that has a higher sensitivity for investigating the thermal and electronic properties of semiconductors than a conventional microphone photoacoustic method [1]. This also gives us an information of non-radiative transitions through deep defect levels. Extensive works for Si, GaAs, and AlGaAs/GaAs samples were carried out [1-3] and a metastable natures for representative deep levels in GaAs such as *EL*2 and *EL*6 were clearly resolved. In the present paper, we propose a model to explaining our experimental results for the non-radiative recombination process in the photoexcited carriers in the AlGaAs/GaAs hetero-structure sample. Annealing effect on the frequency dependence of the PPT signal is also explained by developing the proposed model by Todorović *et al.* [4].

EXPERIMENTAL PROCEDURES AND RESULTS

The samples were the AlGaAs/GaAs hetero-structure semiconductor cut to surface dimension of 7×7 cm^2 from the AlGaAs epitaxial layer grown on a semi-insulating (SI) GaAs substrate wafer. The Si-doped, n-type $Al_{0.2}Ga_{0.8}As$ epitaxial layer (1.4 μm thickness) was grown by the metal organic vapor phase epitaxy (MOVPE) method. The concentration of a shallow Si donor level was 3.0×10^{16} cm^{-3}. The substrate was the carbon-doped, liquid encapsulated Czochralski (LEC) grown SI GaAs (600 μm thickness). The concentrations of deep donor $EL2$ and shallow carbon acceptor in the substrate were 1.3 and 0.4×10^{16} cm^{-3}, respectively. Since the annealing process seems to generate a new defect level in the band-gap [5], two samples, as-grown and annealed (815°C for 30 min in the AsH_3 atmosphere) were prepared for the experiments. The specification of the GaAs substrates was kept constant between two samples.

The experimental configuration involving the sample and the detector is shown in the inset of figure 1. After the sample was cut from the wafer, a disk shaped PZT was attached to the surface of the GaAs substrate using a silver conducting paste. The probing light to measure the PPT signal was mechanically chopped and was always focused on the surface of the epitaxial layer side. The PPT signal generated by the nonradiative electron transitions was detected by the PZT. A detailed experimental setup has already been reported [1].

Figure 1 shows the PPT spectra of AlGaAs/GaAs at 297 K. The PPT signal intensity was recorded as a function of incident photon-energy of the probing light ranging from 1.1 to 2.8 eV. The modulation frequency was set at 200 Hz. Since the same GaAs substrates were used for two samples, the PPT signal amplitudes were normalized below the band-gap (E_g) of GaAs. This

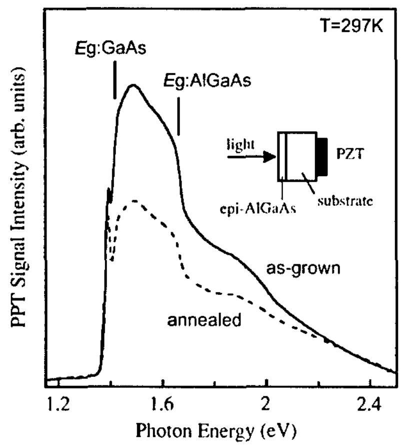

Figure 1. PPT spectra of the AlGaAs/GaAs samples at 297 K. The solid and dashed lines denote the as-grown and the annealed samples, respectively.

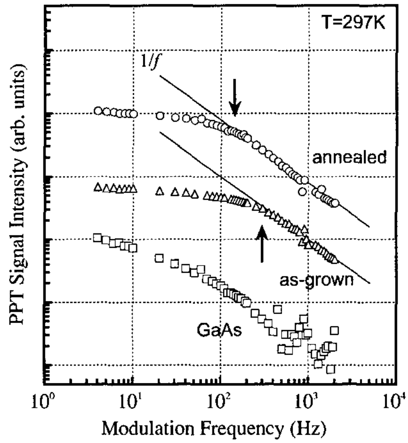

Figure 2. Frequency dependence of the PPT signal of the as-grown, annealed, and the GaAs substrate samples at 297 K.

procedure is reasonable because the PPT signal of LEC-grown SI GaAs below E_g was reported to be due to the electron non-radiative transition involving *EL*2 [2]. As shown in the figure, the PPT signal above E_g of GaAs decreased when the sample was annealed.

In the frequency dependent measurements, the PPT signal at 297 K were, then, measured as a function of the modulation frequency f between 4 and 2000 Hz. The wavelength of the probing light was set at 770 nm ($h\nu$=1.65 eV). Results are shown in figure 2. In this figure, frequency dependence of the PPT signal of LEC-grown SI GaAs substrate sample is also shown. This exhibits almost linear dependence. On the other hand, the deviations from $1/f$ linear function are clearly observed in the AlGaAs/GaAs samples. This critical deviation frequency was found to shift to the lower frequency region by annealing.

DISCUSSION

The PPT signals originated from the AlGaAs epitaxial layer are considerably large compared with that from the substrate. In our previous paper [3], we concluded that electrons photoexcited within the non-doped p-AlGaAs epitaxial layer drifted under the influence of an electric field present at the interface. These drifted electrons eventually recombined with the ionized *EL*2 in the GaAs substrate. In the present case, similar argument is possible. As shown in figure 3, an electric field and band offsets are created at the interface between the n-AlGaAs epitaxial layer and the SI GaAs substrate. Holes photoexcited within the epitaxial layer drifted and eventually recombined with the neutral *EL*2 in the GaAs substrate. Since this transition is known to have a strong non-radiative component [2], the generated heat by this transition causes the PPT signal.

The PPT signals above E_g of GaAs substrate drastically decreased when the sample was annealed at 815°C for 30 min. We, then, assume that the present annealing treatment generates an

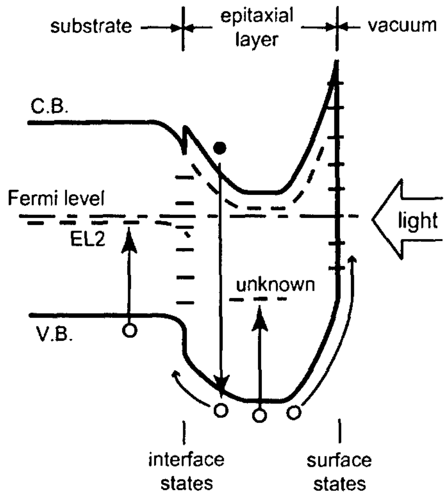

Figure 3. Schematic band diagram near the epitaxial layer and the substrate interface. A depletion region bearing an electric field and band offsets are created.

unknown deep level in the band-gap in AlGaAs epitaxial layer. Supposing that this deep level can act as a faster recombination center for holes, the photoexcited holes cannot drift to the GaAs substrate side. This results in a decrease of the PPT signal intensities in the photon-energy region above E_g of GaAs by annealing is well understood. However, if deep level acts as a non-radiative center, the capturing of the photoexcited hole by an unknown deep level generates a heat and this contributes to increase the PPT signal intensity. This is not the case for the present experimental results.

In the frequency dependent measurements, the incident photon-energy of the probing light was kept at 1.65 eV. Therefore, the signal just below the E_g of AlGaAs was measured. The PPT signal for the SI GaAs substrate exhibits almost linear dependence, as shown in the figure. However, in the AlGaAs/GaAs samples, the deviation from $1/f$ linear function is clearly observed below a critical frequency around 200 Hz. This critical deviation frequency was found to shift to the lower frequency region for the annealed sample.

To explain a shift of the critical deviation frequency observed in figure 2, we develop the theory for the photoacoustic signal generation mechanism proposed first by Todorović *et al.*, hereafter, refer to Todorović model [4]. Note that they have considered that the photoacoustic signal is detected by using a microphone, which is away from the sample surface by the air gap. However, our PZT detector is directly attached to the rear sample surface. Then, such difference should be kept in mind for further discussions. Anyway, we first assume here that the generated PPT signal at the sample surface is completely detected by PZT whichever the signal is caused by a pyro-electric or a piezo-electric effect [1].

In the Todorović model, the photoacoustic signal is caused by following three components, (a) *TD* (thermal-diffusion), (b) *TE* (thermo-elastic), and (c) *ED* (electronic deformation) components. The *TD* component is a consequence of the thermal (heat) diffusion processes in the sample, i.e.,

it depends on the periodic temperature variation on the rear sample surface. The *TE* component is the consequence of the sample surface displacement, that is, the thermo-elastic expansion and bending. This is an important effect in the photoacoustic signal generation mechanism, especially at higher frequencies. Furthermore, the photoexcited free carriers, electron and hole pairs, produce a periodic elastic deformation in the sample directly, so called an elastic deformation (*ED*), which in turn generates the photoacoustic signal. The theoretical calculation due to check a contribution of each three components to the frequency dependence of the PPT signal intensity was carried out. The *TD* component exhibits almost $1/f$ linear dependence. On the other hand, the *TE* and *ED* components show the deviation from $1/f$ linear function below a critical frequency.

In the present experimental frequency region (f=4~2000 Hz), the *ED* component can be neglected because the intensity is very low compared with other components. Therefore, two contributions, *TD* and *TE*, may explain the present experimental results. If the *TE* component becomes dominant than *TD*, a critical deviation frequency is expected to shift to the lower frequency region. This indicates that a bending of the rear sample surface becomes large for the annealed sample than that for the as-grown sample. The photon-energy of the probing light is near the E_g of AlGaAs, and the excess free carriers are generated in the AlGaAs epitaxial layer side. If the unknown deep level fabricated by the sample annealing acts as a non-radiative center and traps the photoexcited hole, the heat generates mainly in the AlGaAs epitaxial layer side. This results in the bending term in the *TE* component may increases. This is a reason for the shift of the critical deviation frequency by the sample annealing.

CONCLUSION

The electron non-radiative recombination processes in n-AlGaAs/GaAs hetero-structure sample were investigated by using the PPT technique. Two types of the samples, as-grown and annealed sample, were used. The PPT signal above E_g of GaAs decreased by sample annealing. From the experimental results, it is considered that the annealing produces an unknown deep level in the band-gap of AlGaAs epitaxial layer. By developing the Todorović theory for the signal generation mechanism, we have explained the experimental results of the frequency dependence. Two contributions, namely thermal diffusion (*TD*) and thermo-elastic (*TE*) components, are considered. The *TE* contribution becomes large for the annealed sample. Since the deep level fabricated by the sample annealing acts as a non-radiative center and traps the photoexcited hole, the heat generates mainly in the AlGaAs epitaxial layer side. This results in the increasing of the bending term in the *TE* component. This is a reason for the shift of the critical deviation frequency by the sample annealing.

Since the PPT method does not necessitate the fabrication of electrodes, the usefulness of this method for studying the electron non-radiative recombination process non-destructively is pointed out. However, more detailed quantitative consideration is necessary for the next step.

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